EVALUATING THE SEISMIC HAZARDS IN METRO MANILA, PHILIPPINES

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ABSTRACT:

We have performed site-specific probabilistic seismic hazard analyses (PSHA) for four sites in the Manila metropolitan area. The Philippine Islands lie within a broad zone of deformation between the subducting Eurasian and Philippine Sea Plate. This deformation is manifested by a high level of seismicity, faulting, and volcanism. The Philippines fault zone is a major left-lateral strike-slip fault that remains offshore east of Manila. The Marikina Valley fault system (MVFS) is the closest active fault to Manila and represents the most likely near-field source of large damaging earthquakes. The largest earthquake that has struck Manila historically, surface wave magnitude (M_S) 7.5, occurred in 1645. Manila has experienced other historical damaging earthquakes numerous times. We have included 14 crustal faults, and the Manila Trench, Philippines Trench, and East Luzon Trough subduction zones (both megathrusts and Wadati-Benioff zones) in our seismic source model. We also have accounted for background crustal seismicity through the use of an areal source zone and Gaussian smoothing. Very little paleoseismic data is available for crustal faults in the Philippines including the MVFS so we have included a large amount of epistemic uncertainty in the characterization of these faults using logic trees. New empirical ground motion predictive equations were used in the PSHA. Based on our analyses, the hazard in the Manila metropolitan area for soil sites and a 2,475-year return period can exceed peak horizontal accelerations of 1.0 g almost solely due to the MVFS. At 1.0 sec spectral acceleration, the MVFS still dominates the hazard in Manila with a small contribution from the Manila Trench megathrust.

KEYWORDS: Probabilistic seismic hazard, Philippines, Marikina Valley fault system

1. INTRODUCTION

The Philippines is a seismically and volcanically active region where damaging earthquakes have struck numerous times within the 400-year historical period (Figure 1). Metropolitan Manila, on the island of Luzon, is the largest urban center, with a population of more than 11 million. The seismically-active Marikina Valley fault system (MVFS) near Manila is a significant seismic source to the city and the region. We have performed probabilistic seismic hazard analyses (PSHA) of four Metro Manila cities: Manila, Quezon City, Taguig, and Valenzuela.

The primary objective of this study was to estimate the future levels of ground motions in the Manila metropolitan area that will be exceeded at a specified probability. Available geologic and seismologic data have been used to evaluate and characterize potential seismic sources, the likelihood of earthquakes of various magnitudes occurring on those sources, and the likelihood of the earthquakes producing ground motions over a specified level. It should be noted that there are very significant uncertainties in the characterization of seismic sources and ground motions in the Philippines due to insufficient research and these uncertainties have been incorporated into the hazard analyses.

2. PSHA METHODOLOGY

The PSHA approach used in this study is based on the model developed principally by Cornell (1968). The calculations were made using the computer program HAZ38 developed by Norm Abrahamson. The program has been validated in the Pacific Earthquake Engineering Research (PEER) Center's "Validation of PSHA Computer Programs" Project (Wong et al., 2004).

Seismic sources are modeled in the hazard analyses in terms of geometry and earthquake recurrence. Three types of earthquake sources are characterized in the PSHA: (1) crustal fault sources; (2) subduction zones (megathrusts and Wadati-Benioff zones); and (3) crustal background seismicity. The crustal background seismicity is addressed in the PSHA through the use of an areal source zone, regions where earthquakes are assumed to occur randomly in the crust, and through spatial (Gaussian) filtering. The megathrusts are modeled as faults and the Wadati-Benioff zones as volumetric sources. Uncertainties in the seismic source parameters, which were often large, were incorporated into the PSHA using a logic tree approach.

To characterize the ground motions as a result of the seismic sources considered in the PSHA, we used empirical attenuation relationships for spectral accelerations. The uncertainty in ground motion attenuation was included in the PSHA by using the log-normal distribution about the median values as defined by the standard error associated with each attenuation relationship. Three standard deviations about the median value were included in the analysis.

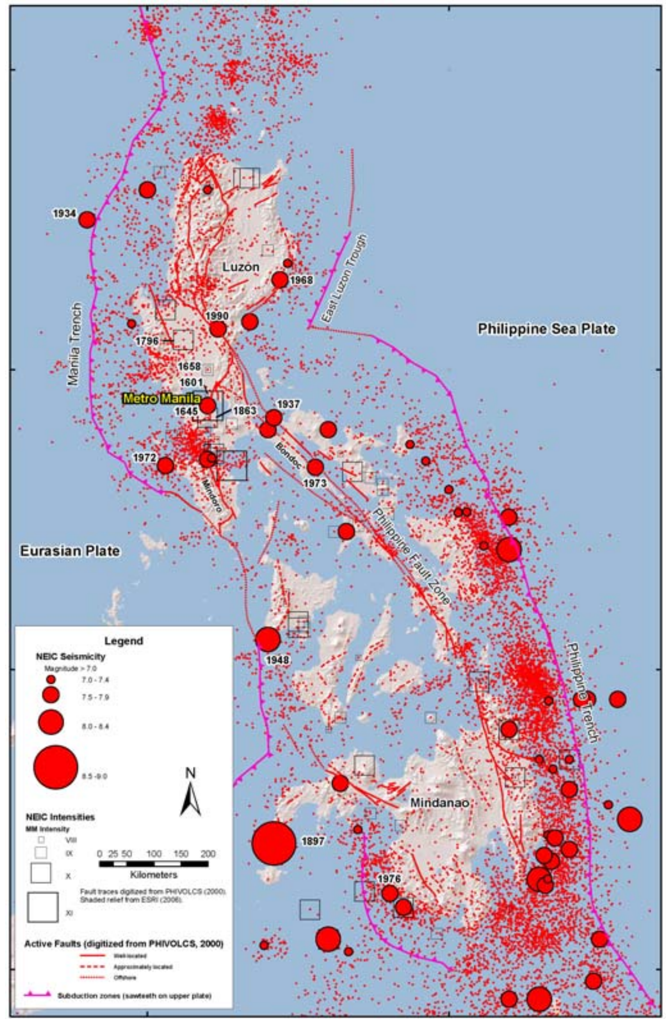

Figure 1 Historical Seismicity (1600 – 2006) and Active Faults in the Philippine Islands

3. SEISMOTECTONIC SETTING AND HISTORICAL SEISMICITY

The Philippines are within a broad zone of deformation between the Philippine Sea Plate to the east and the Eurasian Plate to the west, with convergence accommodated by two opposing subduction systems: the Philippine Trench subduction zone on the east and the Manila Trench subduction zone to the west (Figure 1). The Philippine trench extends from south of Mindanao Island to Luzon Island for a distance of about 1400 km. Near 16° N, the Philippine Trench is separated by a transform fault system that connects it to the East Luzon Trough (Figure 1). Convergence between the Philippine Sea Plate and the Philippine Island arc system is oblique in a northwesterly direction and is estimated to be 28 to 39 mm/yr (Galgana et al., 2007).

The Philippine Islands are within a complex and rapidly deforming area between the two opposing subduction zones. In central Luzon, the Philippine fault zone (PFZ) appears to diverge into several north-south trending splays (Figure 1), and the sense of slip appears to be more compressional than to the south. The highlands of northwestern Luzon Island are the geomorphic expression of this compressional regime. Other major fault systems that

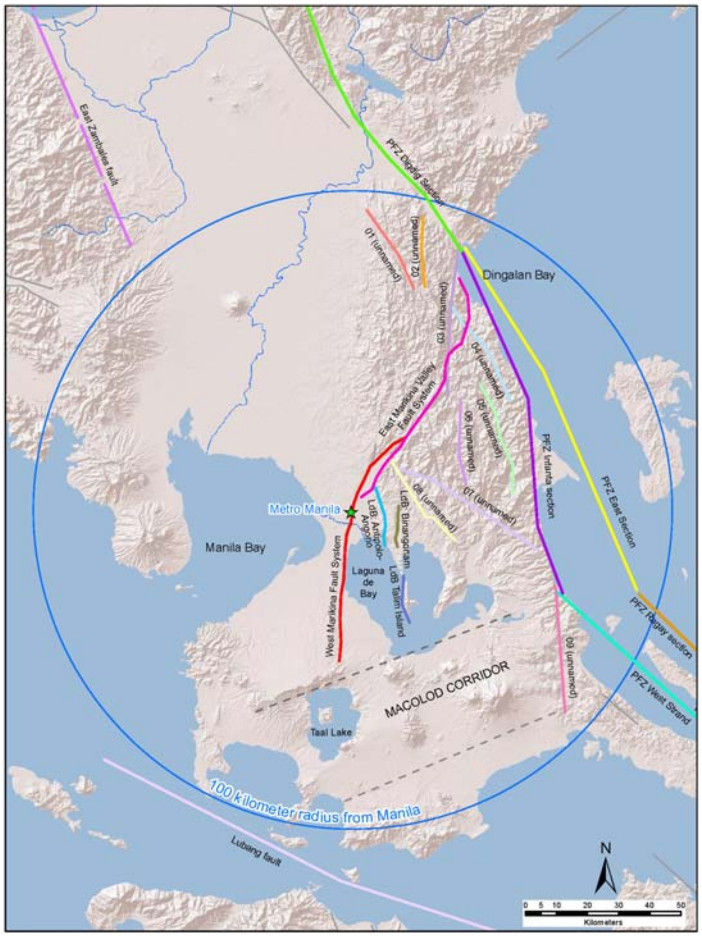

Figure 2. Active Crustal Faults Within 100 km of Manila

accommodate the internal deformation on Luzon Island include the MVFS, the East Zambales fault zone, and the Lubang fault (Figure 2).

The Philippine Islands' location along a major plate boundary almost guarantees that the level of seismicity will be high and earthquakes large (moment magnitude [**M**] > 7). Manila has been heavily damaged by earthquakes at least six times in its 400-year historical record (Repetti, 1946; Nelson et al., 2000). Based on the historical record, more than 50 earthquakes of **M** 7.5 and larger have struck the Philippines (Figure 1). Most notable of these events have been the 1968 surface wave magnitude (M_S) 7.7 Casigman, 1976 **M** 7.9 Mindano, and the 1990 **M** 7.7 Luzon earthquakes.

The largest earthquake to affect Manila was an event on 30 November 1645, estimated to be M_S 7.5 (Figure 1). Tsutsumi et al. (2006) suggest that the sources of the 1645 earthquake were the San Manuel and Gabaldon faults. Damage in Manila was severe, "almost everything crumbled" and the cathedral was destroyed. The number of deaths ranged from 600 to 3,000 (Jagor et al., 2004).

The 16 July 1990 earthquake was the result of rupture of at least 125 km of the northwest segment of the PFZ and its splay the Digdig fault (Figure 2). Structural damage was significant with much of the damage due to surface fault rupture. The event was located about 120 km north of Manila (Figure 2). At least 1700 people were killed and 3500 seriously injured. An earthquake in 1645 also destroyed Manila and may have been the characteristic event preceding the 1990 earthquake. Other damaging earthquakes that have struck Manila occurred in 1601, 1610, 1658, 1675, 1699, 1796, 1824, 1852, and 1863 (Jagor et al., 2004).

4. SEISMIC SOURCES

Seismic source characterization is concerned with three fundamental elements: (1) the identification, location and geometry of significant sources of earthquakes; (2) the maximum size of the earthquakes associated with these sources; and (3) the rate at which the earthquakes occur. In the PSHA we estimated source parameters for the significant faults in the site region, the subduction zones, and an areal source zone and Gaussian smoothing to represent background earthquakes.

Our seismic source model includes all faults identified as active by PHIVOLCS within 100 km of Manila (Figure 2). Additionally, we include the Lubang (Verde Passage-Sibuyan Sea) and East Zambales fault zones, which are located farther than 100 km from the site but are judged to be sufficiently active and are large enough potential seismic sources to warrant source characterization. We also include three subduction zone sources that are in the region and potentially capable of generating great **M** ≥ 8 earthquakes. Generally, the fault sources that are predominantly strike-slip are modeled with vertical planes, although in most cases data on the dips of these faults are not available. For the rupture depth we have adopted 25 ± 5 km, which is taken from the preferred locking depth in the kinematic model of Galgana et al. (2007). The 1990 **M** 7.7 Luzon earthquake had an average rupture depth of 20 km (Yoshida and Abe, 1992), also suggesting that Luzon has a relatively thick seismogenic crust that can be assumed for other faults within the region.

We calculate preferred maximum magnitudes for the crustal faults or fault segments using the empirical relationships developed by Wells and Coppersmith (1994) between **M** and surface rupture length and empirical relationships developed by Hanks and Bakun (2002) between **M** and rupture area (RA in km^2), which are weighted equally. For the subduction zones, we calculate the preferred maximum magnitude using the empirical relations between rupture area and moment magnitude by Abe (1981) and Geomatrix Consultants (1993).

Uncertainties in determining recurrence models can significantly impact the hazard analysis. We considered characteristic and maximum-magnitude recurrence models, with various weights depending on the source geometry and type of rupture model. We favored the characteristic model for all crustal fault sources (weight of 0.70) while the maximum magnitude model was weighted 0.30. The characteristic and maximum magnitude models were weighted 0.6 and 0.4, respectively, for subduction zones. The global average *b*-value of 1.0 was used for the exponential portion of the truncated-exponential and characteristic models for the subduction zones.

4.1. Crustal Faults

The crustal faults in our seismic source model included the PFZ, Laguna de Bay fault system, Lubang fault zone, East Zamfales fault, and several unnamed faults (Figure 2). The MVFS is described below.

The MVFS is the closest active fault to the Manila metropolitan region and represents the most likely near-field source of large, damaging earthquakes to Manila. The MVFS extends 135 km from where it splays away from the PFZ near Dingalan Bay in the north to the Macolod Corridor, a zone of active volcanism, in the south (Figure 2). The MVFZ is thought to be a predominantly right-lateral strike-slip fault that is conjugate to the left-lateral PFZ. At a gross map scale, the fault zone has three distinct sections. The eastern section, referred to as the Eastern Marikina Valley fault (EMVF), extends southeast 75 km from Dingalan Bay to the northern Marikina Valley. The northern Marikina Valley is interpreted as a releasing stepover (Nelson et al., 2000), with the EMVF bounding the east side of the valley. Bounding the west side of the valley is the Western Marikina Valley fault (WMVF), which extends an additional 70 km south through metropolitan Manila until it becomes obscured by young volcanic deposits of the Taal Volcano in the Macolod Corridor volcanic zone (Figure 2). A third zone of discontinuous active faults, named here the Laguna de Bay fault system, splays off of the EMVF near the southern end of the EMVF-WMVF stepover and trends N-S for nearly 50 km, with west-facing escarpments, forming the western margin of Talim Island in Laguna de Bay.

Although the MVFS represents a high-hazard fault to Manila, relatively little is known about the amount of total offset, slip rate, average recurrence of large earthquakes, and extent of past ruptures along the fault. Rimando and Knuepfer (2006) conducted a study of the fault in order to characterize the geomorphic expression of the fault, document displacements, and divide the fault into segments based on structural, geomorphic, and geometric criteria. Their study divides the fault into ten fault sections based largely on morphology and structural observations, with one section, the Sucat-Biñan section, subdivided based on observations of possible fault creep.

The paleoseismic investigation of Nelson et al. (2000) provides the only information on the timing of earthquakes along the MVFS. The Maislap trench site is located at the northern end of the stepover between the WMVF and the EMVF and records two to four surface-rupturing earthquakes during the past 1300 to 1700 years, with a preferred recurrence interval of 400 to 600 years. Nelson et al. (2000) infer the most recent event to have occurred during the historical period, possibly correlating with one of the earthquakes that affected the area in A.D. 1599, 1601, 1658, 1700, 1766, or 1863. Although Nelson et al. (2000) were not able to resolve lateral slip related to any of the events seen in the trenches, they speculate that, based on an assumed ratio of horizontal to vertical slip, the vertical slip seen along the faults in the trench exposures indicates lateral slips of 1 to 2 m during each event. However, Rimando and Kneupfer (2006) note that the trenches may have not crossed all of the active fault strands in the area and that this may be a minimum value for slip-per-event. Rimando and Kneupfer (2006) estimated a slip rate of 5 to 7 mm/yr for the WMVF and 6 to 8 mm/yr for the EMVF. One potential issue with the location of the Maislap site within the stepover between the WMVF and the EMVF is it is unknown if the events observed in the trenches occurred on the WMVF, the EMVF, or involved both faults.

4.2. Subduction Zones

There are three subduction zones included in the PSHA. The most significant subduction zone, the Manila Trench subduction zone, is a 1,000 km-long zone between Taiwan and Mindoro Island in the Philippines. It is characterized by an east-dipping Wadati-Benioff zone that extends to ~200 km depth (Hamburger et al., 1983). Kinematic and geodetic studies indicate that Eurasia-Philippine Sea Plate convergence is accommodated primarily along the Manila Trench, and a lesser amount occurs along the East Luzon Trough and Philippine Trench (Galgana et al., 2007). Seismicity also indicates that the Wadati-Benioff zone varies from moderately dipping along the central part of the subduction zone to near vertical at both ends of the Manila Trench (Hamburger et al., 1983).

Historically, the Manila Trench has had few large magnitude earthquakes. Only two **M** > 7 earthquakes have occurred west of Luzon during the past 100 years, in 1934 and 1948 (Figure 2), and both are poorly located with respect to the subduction zone (Hamburger et al., 1983). Rowlett and Kelleher (1976) suggest that the 1948 earthquake was seaward of the trench, possibly related to intraplate faulting. Although the location of the 1934 **M** 7.6 earthquake is poorly constrained, it is close to where the Manila Trench changes trend from being more north-south, south of 18° N, to northwest north of this latitude (Figure 2).

We consider two scenarios in our source characterization: the first scenario involves a full rupture of the Manila Trench megathrust, a rupture length of about 1000 km. The width of the locked zone of the megathrust is unknown. However, we can use the distribution of seismicity to estimate the size of the locked zone. In our model, we assume that the zone between the trench and the area of increased seismicity represents the locked zone, a down-dip rupture width of about 90 km. Using the rupture length, down-dip width of the seismogenic zone and magnitude area relationships, we calculate that a full megathrust earthquake would have a magnitude of **M** 8.8.

The alternative model is a segmented Manila Trench megathrust. Our segmentation is largely based on a ~35 degree change in the trend of the Manila Trench off the coast of northern Luzon. The southern section of the Manila Trench trends for about 560 km north-south, while north of Luzon the trench trends more northwesterly. This change in trend also may coincide with where the Wadati-Benioff zone becomes more steeply dipping to the south. Between 18° N and 13.5° N, Barrier et al. (1991) contour the top of the Wadati-Benioff zone with a dip of about 30 to 35 degrees. Using this dip, and an assumed depth of 30 km for the locked zone, gives a down dip width of 52 km. The empirical relationships give an estimated magnitude of **M** 8.4. Using the shallower dip and a rupture length of 440 km, the magnitude-area relationship gives a magnitude **M** 8.5 for large earthquakes along the northern section of the megathrust. Although other rupture scenarios are possible, the lack of any historical seismicity or paleoseismic records to help constrain the size and extent of past megathrust earthquakes limits our ability to ascertain whether alternative scenarios are viable.

All three subduction zones appear to have active Wadati-Benioff (intraslab) zones although the Luzon intraslab zone is not very active. The intraslab zones are modeled as stair-casing blocks 20 km thick and 30 to 40 km wide. The maximum magnitude assumed for each zone was **M** 7.5 ± 0.3. This value is typical of intraslab zones and is consistent with the historical record (Figure 2). Recurrence parameters (*a*- and *b*-values) were calculated from the historical record. The truncated exponential model was assumed. The recurrence relationships were estimated using the maximum likelihood procedure developed by Weichert (1980) and the estimated completeness intervals for the region. Dependent events also were identified and removed from the catalog.

4.3. Crustal Background Earthquakes

The hazard from background (floating or random) earthquakes that are not associated with the known or mapped faults must be incorporated into the hazard analysis. Earthquake recurrence estimates in the site region and maximum magnitudes are required to assess the hazard from background earthquakes. In tectonically active areas such as the western U.S., the maximum magnitude for earthquakes not associated with known faults usually ranges from **M** 6 to 7 depending on the thickness of the seismogenic crust. In this study, we adopt a value of **M** 7 ± ¼. The earthquake recurrence was calculated in the same manner as for the intraslab zones. The crustal background seismicity was assumed to be uniformly distributed throughout the Luzon region.

5. GROUND MOTION ATTENUATION MODELS

To characterize the attenuation of ground motions from crustal sources in the PSHA, we have used recently developed empirical attenuation relationships appropriate for tectonically active regions. These new PEER Next Generation Attenuation (NGA) models benefited from a significant increase in strong motion data from large (**M** > 7) earthquakes at short distances (< 25 km). The four relationships used with equal weights were: Abrahamson and Silva (2008), Chiou and Youngs (2008), Campbell and Bozorgnia (2008), and Boore and Atkinson (2008).

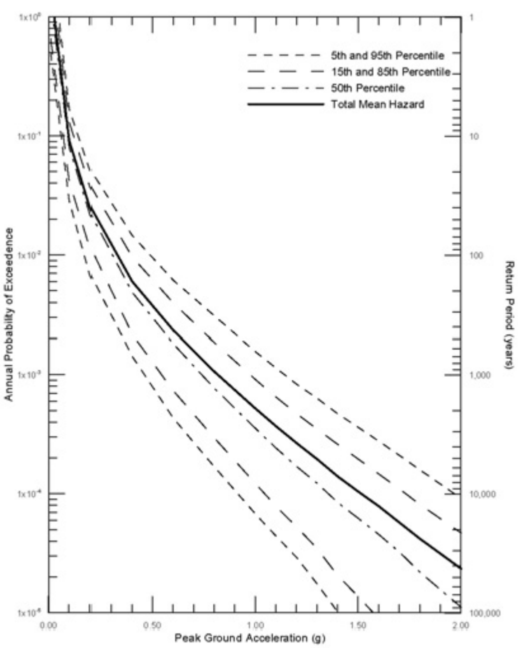

Figure 3. Seismic Hazard Curves for PGA for Quezon City

For megathrust sources, the Youngs et al. (1997), Atkinson and Boore (2003), and Gregor et al. (2002) attenuation relationships were used and weighted 0.4, 0.4, and 0.2, respectively. Gregor et al. (2002) was weighted lower because it is based on numerical modeling. For intraslab sources, the Youngs et al. (1997) and Atkinson and Boore (2003) attenuation relationships were used and equally weighted. All relationships provide the attenuation of peak horizontal ground acceleration (PGA) and response spectral acceleration (5% damping).

Forward rupture directivity along the MVFS has been included in the hazard calculations. The PSHA code HAZ38 includes the directivity models by Somerville et al. (1997) and Abrahamson (2000). The hypocenter is randomized over the rupture plane given that *a priori* knowledge of the point of rupture initiation is unavailable.

6. PSHA RESULTS

Table 1. PGA Hazard

Return Period	475 Years	2,475 Years
Manila	0.42 g	0.69 g
Quezon City	0.62 g	1.07 g
Taguig	0.57 g	1.02 g
Valenzuela	0.36 g	0.57 g

The results of the PSHA are presented in terms of ground motion as a function of annual exceedance probability. This probability is the reciprocal of the average return period. For example, Figure 3 shows the mean, median (50th percentile), 5th, 15th, 85th, and 95th percentile hazard curves for PGA. These fractiles indicate the range of epistemic uncertainties about the mean hazard. Table 1 summarizes the PGA hazard at the four Metro Manila cities. At a typical building code return period of 2,475 years, the mean PGA ranges from 0.57 g to 1.07 g. Proximity to the MVFS is controlling the hazard. The site in Quezon City is located adjacent to the WMVF, which accounts for the higher hazard there.

Deaggregation by source shows that the high-frequency hazard as reflected in PGA is dominated by the MVFS at all return periods for Quezon City. At longer period ground motions, > 1.0 sec SA, the MVFS also controls. By deaggregating the hazard by magnitude and distance bins, Figure 4 illustrates the PGA hazard contributions in Quezon City for the return period of 2,475 years. The hazard is coming from events of **M** 6.5 to 7.6 at distances of less than 10 km corresponding to events from the WMVF.

Horizontal Uniform Hazard Spectra (UHS) were calculated for a return period of 2,475 years for Quezon City (Figure 5). The UHS shows the impact of forward rupture directivity at periods greater than 0.5 sec. We also performed the PSHA for soft rock (V_S30 520 m/sec) to see the differences in ground motions from soil assuming a V_S of 310 m/sec. As can be seen, the soil has a slightly lower PGA and is lower out to 0.4 sec due to soil nonlinearity (Figure 5). The soil spectral peak is shifted to longer period as expected and the spectrum is amplified compared to the rock values beyond 0.4 sec. The differences are not as significant as one might expect probably due to the high ground motions (PGA > 1 g) being damped out due to soil nonlinearity.

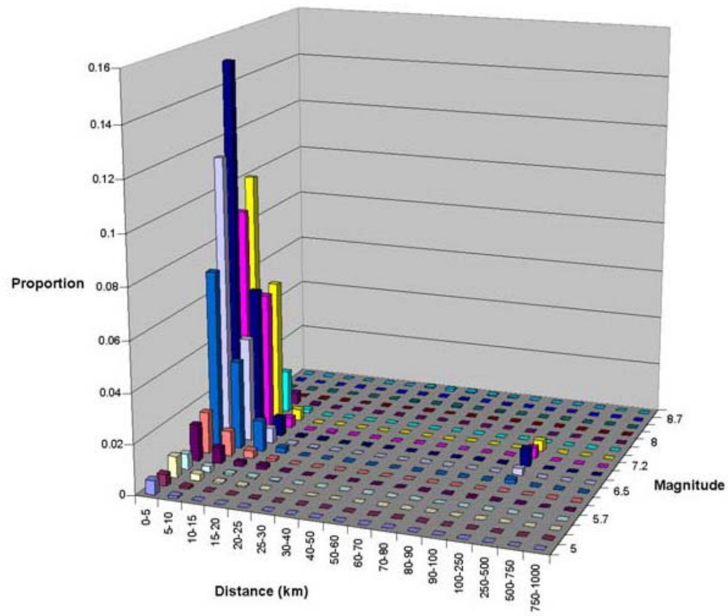

Figure 4. Magnitude and Distance Contributions to the Mean PGA Hazard at a 2,475-Year Return Period for Quezon City

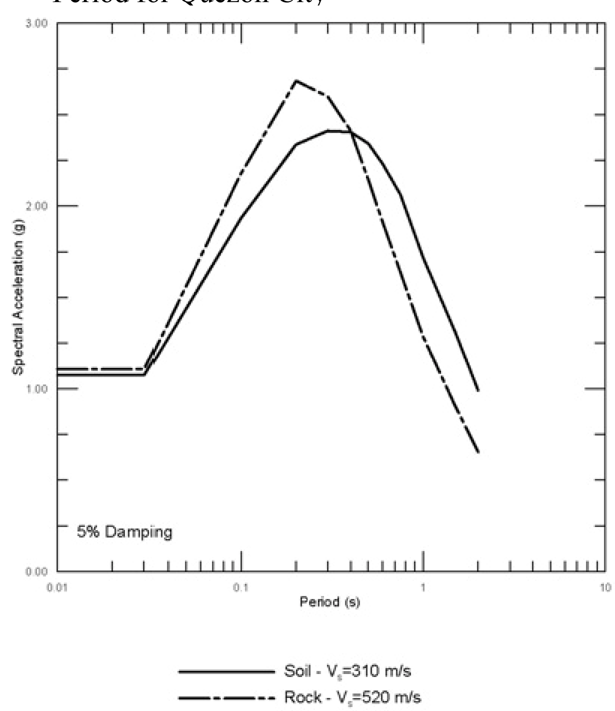

Figure 5. 2,475-Year Return Period Soil and Rock Horizontal UHS for Quezon City

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